NETWORK ENGINEERING AND IMPLEMENTATION

The 70-meter Antennas

Reporting on the maintenance, rehabilitation, and upgrade of the DSN 64-meter antennas in March 1982,[35] the DSN chief engineer, Robertson Stevens, focused attention on the history and status of the hydrostatic azimuth bearings and azimuth radial bearings, particularly those at DSS 14 and DSS 43. He also recommended a plan for continuing repair or replacement of components and the continuing upgrade of maintenance and operating procedures. The report also argued convincingly that it was indeed practical to enlarge the antennas to 70-meter diameter and to extend the useful operating frequency for these antennas.

Over the next several years, while the Network continued to support all flight missions described in the previous chapter, these recommendations were implemented. This work included the three 70-m upgrades, the last of which was completed at DSS 14 in May 1988.

By 1989, the Goldstone antenna had been in continuous operation for 23 years, and the overseas antennas had been in operation for 16 years. The specified design life for parts subject to wear was 10 years. The antennas had been specified and designed more than 27 years earlier. They had performed remarkably well, but with a resurgence in the number of planetary missions planned for the Galileo Era, even more was to be demanded of them.

To this end, a DSN Antenna Rehabilitation Team[36] was established in March 1989 to identify the resources needed to maintain the new 70-m antennas past the year 2000. The team recommended five high-priority tasks it believed would, if promptly implemented, extend the useful operating life of the antennas for the next twenty-five years.

The tasks were to develop a trend analysis program to provide early detection of incipient failures; to provide a means of lifting the antenna in the event that a pad or ball joint needed to be replaced, as had occurred in Spain and Australia in 1976; to repair or replace aging structural and mechanical elements of the antenna before further deterioration took place; to rehabilitate the elevation and azimuth gearboxes, since the gear drive assemblies ranked next to the hydrostatic bearing in the number of problems experienced over the years; and to replace the subreflector positioner and controls because these had been a longstanding source of trouble.

The hydrostatic bearings at Spain and Australia were believed to be in good condition and were not expected to require any special attention in the foreseeable future. However, there was less confidence in the future of the hydrostatic bearing at Goldstone. It was hoped that existing procedures to inhibit rust formation would be successful and that major rework would not be necessary. Only time would tell.

It was the opinion of the team that the basic design was sound and that, under normal operating conditions, the structure was not subjected to high stress levels. At the time, cyclic stresses were considered to be infrequent and of a low level, so fatigue or catastrophic failure was thought to be unlikely.

Elevation Bearing Failure

About the time that the 70-m Rehabilitation Team was publishing these findings (November 1989), the *Galileo* spacecraft was reaching the point where it became dependent on continuous support from the 70-m antennas to sustain the downlink telemetry data rate of 1,200 bps needed for its rapidly approaching Encounter with Venus on 9 February 1990. Closest approach would occur during the DSS 43 overlap with DSS 63, and full 70-m coverage was essential to the success of this first gravitational-assist event in the *Galileo* mission to Jupiter. On 13 December 1989, in the midst of this intense 70-m activity, the right-side inboard elevation bearing on the DSS 63 antenna failed, and the antenna was immobilized.

The failure occurred about 9:00 a.m. (local time) while the antenna was being used to investigate some anomalous Doppler problems at low elevation angles. It appeared that one or more of the rollers in the roller bearing race that supported the right inboard elevation bearing had cracked. The bearing sustained further damage when the antenna was driven back to the zenith position for safety. The extent of the damage can be appreciated by the photograph of the damaged bearing shown in Figure 5-25.

Obviously, a very serious antenna bearing problem now existed. The situation was exacerbated by pressure from *Galileo*, the approaching holidays, and arduous working conditions due to inclement winter weather in Spain.

The DSN immediately dispatched several antenna engineers to Madrid to investigate the problem. Dale Wells, one of the engineers involved in the mechanical maintenance of all three large antennas since they were first built, remained on site to direct the repair work, while other technical staff at JPL coordinated the shipment of spare bearings and other parts.

The unusual nature of the repair work required special tooling, much of which was fabricated on site. The right side bearing, carrying two million pounds of antenna weight, was lifted with hydraulic jacks, and removal of the damaged bearings began. This proved

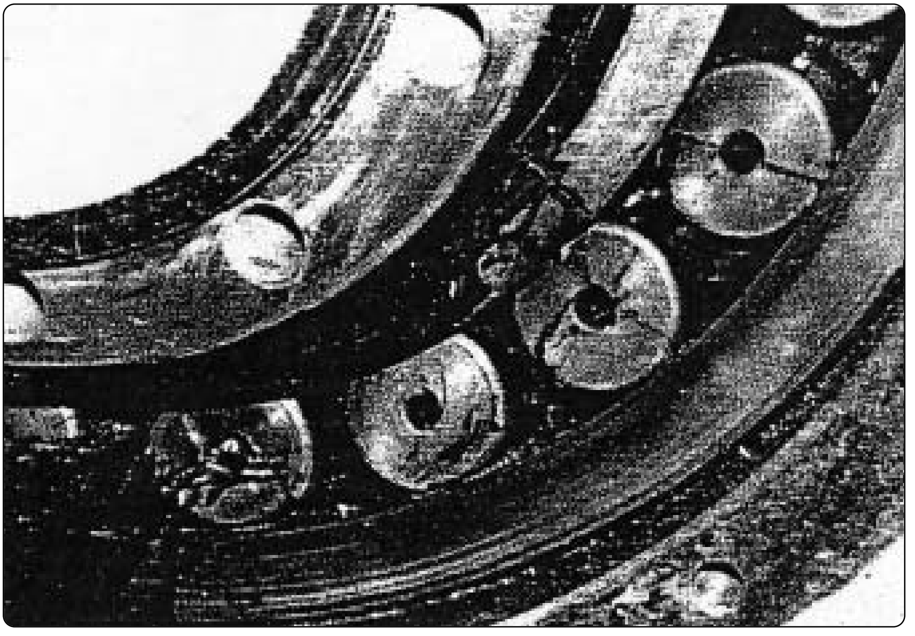

Figure 5-25. Cracked bearing rollers and inner race, DSS 63, December 1989.

to be extremely difficult and was eventually accomplished by flame-cutting some of the retaining bolts and sections of the damaged race. Once the old bearing parts were removed, installation of the new bearings proceeded rapidly, and the antenna was tested and returned to service on 25 January, fifteen days before the *Galileo* encounter with Venus. The broken bearing was carefully reassembled and returned to JPL for evaluation.

An Elevation Bearing Failure Team was formed in January to investigate the DSS 63 failure and to oversee any remedial action that might be needed at the other 70-m antennas. The team first decided to return the broken bearing to SKF for a bearing failure analysis. There, it was determined that the failure had been caused by fatigue of the inner bearing rollers, which, over the years, had caused metal particles to flake off and damage the surfaces of other rollers in the bearing. This progressive action ultimately led to complete lockup of one roller, and eventually to failure of the entire bearing race.

Following the DSS 63 return to service, the elevation bearings on all the 70-m antennas (including those at DSS 63) were inspected in sequence for signs of wear. Some signs of wear were found, but none that warranted a change of the bearing races at that time. It was decided to continue with regular analysis of bearing for detection of metal particles. This work, requiring only two days of antenna downtime at each site, was carried out during April and May of 1990.

The team also directed that the loads on each of the inboard and outboard elevation bearings on all three antennas be equalized to correct the additional, unequal loading that resulted from the 70-m upgrade. This work was sufficiently important to require 21 days of antenna downtime, beginning immediately at DSS 63. It was fortuitous that the *Galileo* spacecraft was approaching its first Earth fly-by around this time, and consequently its need for 70-m support was minimal. The work was completed at DSS 14 in January 1991. In some cases, before the load equalization adjustment, the inequality of load sharing between the inner and outer bearings was as much as 80 percent to 20 percent. With the work completed, this was reduced to, typically, 55 percent to 45 percent or better.

Finally, the Team recommended that the original roller bearings, which were manufactured with 3/4-inch axial holes to facilitate the heat treatment process, should be replaced with solid roller bearings. Orders for new bearings were placed, and the work of replacement began in May 1991 at DSS 63. Using their experience and tooling from the previous bearing replacement effort, the engineers completed the work in just 17 days. To economize on antenna downtime, replacement of the elevation bearings at DSS 43 and DSS 14 was carried out in 1993 and 1994, in conjunction with the upgrade of the elevation gearboxes.

Gearbox Rehabilitation

The primary motive power to drive the huge 70-m antennas in the azimuth and elevation directions is provided by hydraulic motors activated by computer-controlled servo systems. The high-speed output shafts of the hydraulic motors are connected to the various low-speed gears (pinions) and quadrants. These physically rotate the antenna by using reducer gearboxes—four for the elevation drive and four for the azimuth drive.

Ever since the antennas were first built, persistent problems with the gearboxes had been constant cause for concern and led to expensive and antenna-time consuming repair efforts. Until about 1984, most of the gearbox problems were related to lubrication matters, but in 1985, a significant increase in the wear patterns on all antenna drive components, particularly the gearboxes, became evident. This was attributed to the introduction of the 1985 Mark-IVA servo modifications described in the previous chapter. The new servos drove the antennas at maximum velocity between the "stow" and "track" positions, and vice versa, causing additional wear and even inducing oscillations in the overall system. In addition, the increasing DSN tracking schedule in that period called for more rapid changes between multiple spacecraft; also, VLBI, clock synchronization, and Star Catalogue passes required frequent and rapid slewing of the antennas, with fast starts and stops.

By 1986, the situation had become serious enough on the DSS 14 antenna to warrant an examination and evaluation of wear on the elevation bull gear and pinion by a professional consultant from the University of California at Berkeley. On the basis of this evaluation, the elevation pinion gears at DSS 14 and DSS 43 were replaced with specially hardened gears in 1987 as part of the 70-m upgrade. Gear replacement was not required at that time at DSS 63. In April 1988, an expert consultant specializing in gear train systems was sought to examine and report on the condition of the gearboxes themselves. The two specific recommendations called for replacing the drive train gearbox components with case-hardened and precision-ground gears, and adding magnetic particle detectors to the lubrication systems to remove wear debris. DSN engineers responded with a contract to the Philadelphia Gear Company in 1990 for a completely new set of components to upgrade or replace the existing 24 gearboxes on all three 70-m antennas. The new design incorporated the experts' opinion and the DSN engineers' experience with the original design, which had provided approximately thirty years of continuous operational service.

Installation of the new gearboxes began with DSS 43 in March 1993 and proceeded around the Network as downtime could be scheduled, to DSS 14 in September 1993 and DSS 63 in June 1994.

Subreflector Drive Problems

The considerations that led the 70-m Antenna Rehabilitation Team in 1989 to recommend complete replacement of the subreflector suspension and drive systems resulted from the inadequate design of the 70-m components. Constrained in many ways by the design of the former 64-m components, they simply were not robust enough to handle the much larger and heavier subreflector used on the 70-m antennas. Frequent failures and problems occurred, and several modifications and temporary work-arounds were necessary to keep the antennas in operation. Because the estimated cost of the work was 3.6 million dollars, budget constraints at the time prevented the recommendations from being implemented immediately, and the matter was deferred.

However, before anything more could be done in this regard, nature itself intervened. On Sunday 28 June 1992, just as the DSS 14 antenna was being rotated to the horizon in preparation for a *Pioneer 10* spacecraft track, the Goldstone area was hit by two severe earthquakes within a few hours of each other.

In the shaking that followed, the 24,000-pound subreflector broke loose from the three-axis drive shaft and impacted the quadripod suspension structure. The cast aluminum subreflector was severely damaged, and its precision-contoured surface was cracked and holed. All antennas at Goldstone were halted while damage was assessed. As it turned out, only DSS 14 had sustained permanent damage, and repair started immediately. At first it was thought that the subreflector would have to be replaced, and action was started to ship the fiberglass subreflector that had been used several years earlier at DSS 43. However, it was eventually decided that the subreflector and its drive system should be repaired in place, over 71 meters above the ground, with the antenna at zenith. Over the next three weeks, all the damaged parts of the subreflector and its three-axis drive system were either repaired or replaced, and the antenna was returned to full operation on 22 July 1992. After necessary mechanical and optical realignment adjustments were made, it was estimated that the loss of RF gain attributable to damage inflicted by the earthquake (and subsequently repaired) was no greater than 0.06 dB at X-band. This small performance loss was within acceptable limits, and the antenna was approved for full operational use.

On 1 July 1992, right after the earthquake occurred, an Engineering Analysis and Corrective Actions Team was formed to analyze the damage, assist with the return to service actions, and recommend corrective action to improve the protection of the 70-m antennas from future earthquake damage. In 1995, as a result of the team's findings, new earthquake-resistant subreflector positioners were designed, built, and installed on all 70-m antennas. The 70-m antenna mechanical specifications were changed to better match an earthquake-prone environment, and future antenna designs reflected the need for seismic protection. Seismic monitoring procedures were established for the Goldstone antenna using accelerometer sensors located at strategic points in the base and apex areas of the antenna.

There have been no further earthquake incidents in the DSN as of this writing.

Toward the end of the Galileo Era, the funds available for antenna maintenance were significantly affected by overall reductions in the DSN budget. Out of this situation, yet another review board emerged to report on the physical condition of the 70-m and 34-m antennas. Based on these findings, the board was to recommend cost-effective measures that would assure their continued reliable operation in the forthcoming period of diminished resources.

The board was chaired by Richard P. Mathison, then chief engineer, and included several experts from the National Radio Astronomy Observatory (NRAO) with experience in large antennas, and some with knowledge of telescope (Keck) mounting structures.

In late 1996, the board inspected the antennas at each of the three sites and closely examined specific onsite maintenance problems with the engineers involved.

The board concluded that the condition of the antennas and the level of maintenance at all sites was uniformly good. It expressed concern for incipient failures in several of the steel and concrete elements of the 70-m structures and recommended a continuing program of monitoring and inspection to establish trends in performance deterioration. To reduce antenna maintenance costs, the board suggested that the DSN should clearly establish an absolute minimum level of maintenance required for reliable operation for all 70-m antennas. This would enable proper allocation of funding between the requirements for minimum maintenance, preventative and corrective maintenance, and the replacement and procurement of spare parts.

In 1997, it was generally believed that the 70-m antennas were in sound mechanical condition, that their potential structural and mechanical weaknesses were well understood and under control, and that with the recommendations of the Mathison Review Board in effect, they would continue to provide reliable uplink and downlink service well into the new century.

Interagency Arraying

Parkes-Canberra Telemetry Array

As early as 1981, advanced systems planners in the DSN had begun to evaluate the possibility of enhancing the downlink performance of the DSN 64-m antennas for special, short-duration mission events of high science value, such as the future Voyager Encounters with Uranus and possibly Neptune, by arraying other large, non-DSN antennas with those of the DSN. These ideas followed naturally from the DSN's long history of arraying with its own 64-m and 34-m antennas, summarized in Figure 5-26.

Because of its past associations with the DSN and reasonably close proximity to Canberra, the 64-m antenna of the Radio Astronomy Observatory in Parkes, New South Wales, Australia, was the first non-DSN antenna to be considered for this purpose. This facility, owned and operated by the Australian Government's Commonwealth Scientific and Industrial Research Organisation (CSIRO), formed the basis for much of the early design work on the DSN's own 64-m antennas twenty years earlier.

After the necessary high-level agreements between CSIRO and NASA were completed, a technical design for a Parkes-CDSCC Telemetry Array (PCTA) was initiated.[37] At that

Mission	Date[a]	Location of antennas	Antenna types	Combiners[c]
Pioneer 8	1970	Spain	26-m + 26-m	Passive BB
Mariner Venus-Mercury (Mercury)	Sept. '74	U.S.	64-m + 2 (26-m)	R&D BB
Voyager 1 (Jupiter)	Mar. '79	U.S.	64-m + 34-m	RTC
Voyager 2 (Jupiter)	Jul. '79	U.S.	64-m + 34-m	RTC
Pioneer 11 (Saturn)	Sep. '79	U.S.	64-m + 34-m	RTC
Voyager 1 (Saturn)	Aug. '80	ALL DSCCs	64-m + 34-m	RTC
Voyager 2 (Saturn)	Aug. '81	ALL DSCCs	64-m + 34-m	RTC
International Cometary Explorer (Giacobini-Zinner)	Sep. '85	ALL DSCCs Spain/U.S. Australia/Usuda	64-m + 34-m[b] 64-m + 64-m 64-m + 64-m	Passive BB SSRC R&D SSRC R&D
Voyager 2 (Uranus)	Jan. '86	Spain U.S. Australia	64-m + 34-m 64-m + 2 (34-m) 64-m + 2 (34-m) +Parkes 64-m	RTC/BBA RTC/BBA RTC/BBA + LBC + SSRC R&D
Voyager 2 (Neptune)	Aug. '89	Spain U.S. Australia	70-m + 2 (34-m) 70-m + 2 (34-m) + VLA 27 (25-m) 70-m + 2 (34-m) +Parkes 64-m	RTC/BBA RTC/BBA + VLBC + SSRC RTC/BBA + LBC + SSRC

[a] Listing of month and year indicates encounter period.
[b] The Spain and U.S. 64-m antennas also combined dual channels with passive BB.
[c] BB = Baseband (symbol-modulated subcarrier).
LBC = Long Baseline Combiner (baseband at ~300 km).
RTC = Real-Time Combiner, first version (baseband at ~30 km).
RTC/BBA = Operational RTC—part of BBA (Baseband Assembly).
SSRC = Symbol-Stream Recording and Combining (non-real time).
VLBC = Very Long Baseline Combiner (baseband at ~1,000 km).

Figure 5-26. Twenty years of telemetry arraying in the DSN.

time, the PCTA was designed specifically to meet the downlink requirements of the January 1986 Voyager Encounter with Uranus. It was estimated that the addition of the 64-m Parkes antenna to the CDSCC configuration of one 64-m antenna arrayed with two 34-m antennas could increase the downlink capability for the Voyager/Uranus Encounter by as much as 50 percent.

Prior to NASA's becoming interested in seeking the support of CSIRO for the use of the Parkes antenna for Voyager, the European Space Agency (ESA) had already completed similar agreements for Parkes support of the Giotto mission to Comet Halley. The antenna had been in service for twenty years, and a major upgrade to its facilities, computers, and servo and pointing capability had just been completed. Under this agreement, CSIRO would further upgrade the antenna for operation at X-band. Fortunately for NASA, the ESA X-band configuration for Giotto was compatible with the configuration required for Voyager, and arrangements were made with CSIRO for the two agencies to share antenna equipment and tracking time from late 1985 through the encounters with Uranus and Comet Halley in January and March 1986.

The low-noise, X-band receiving equipment that was to be shared consisted of a feedhorn provided by CSIRO, a microwave assembly provided by JPL, and two masers built in the U.S. to the standard JPL design with funding provided by ESA. The front-end equipment package was integrated with French designed down converters by ESA at Darmstadt, West Germany. A video-grade microwave link, of Japanese manufacture, was supplied by Telecom Australia, to transfer the Parkes data stream to the Canberra Complex, some 350 km distant, for combining with the DSN data stream.

At first, DSN engineers, with their long history of successful in-house experience, viewed the international flavor of the PCTA front-end package with some reservation. However, its performance under actual operational conditions left no room for skepticism, and it performed well for many years afterward, with a minimum of problems.

The functional block diagram of the Parkes-CDSCC Telemetry Array shown in Figure 5-27 identifies the various areas of responsibility among the DSN, ESA/Parkes, Telecom Australia, CSIRO/Parkes, and the PCTA at Parkes and CDSCC.

As might be expected, the transmission time delay on the 350-km microwave link from Parkes to Canberra introduced additional complexity to the combining process. The delay was found to be quite stable and equal to 1.2 milliseconds. The effect of this and other more subtle dynamic delays was provided for by special circuits in the design of the Long Baseline Combiner.

Most of 1983 was occupied with negotiating the unique NASA-ESA-CSIRO agreements and developing interface design control specifications to ensure that all the elements of the PCTA would work together when assembled end-to-end. In 1984, fabrication of the individual elements, including implementation of the intersite microwave link, was in progress. Testing and verification for compatibility with each other and with the Voyager

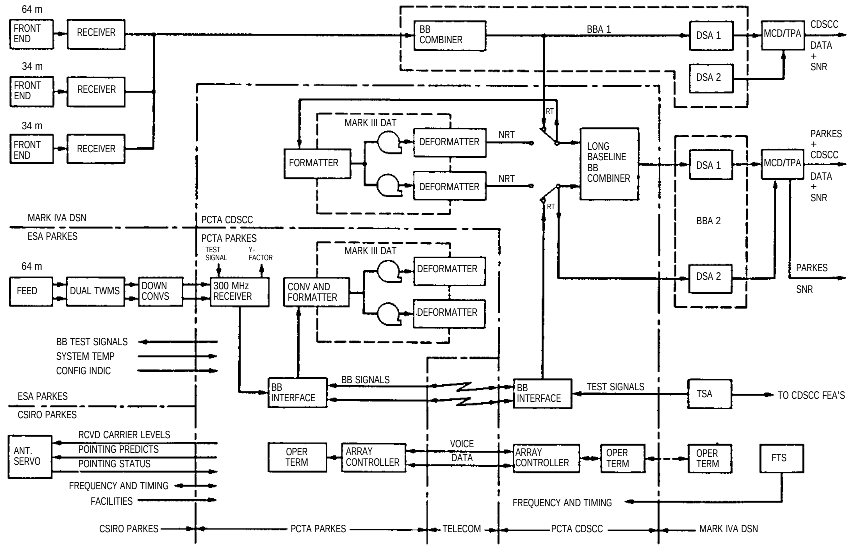

Fig. 2. Parkes=CDSCC Telemetry Arry, functional block diagram

Figure 5-27. Parkes-CDSCC telemetry array. In this diagram, the amplified X-band downlink signals from the antennas at Parkes and CDSCC were first changed down to the 300-MHz band to feed the receivers which delivered baseband (subcarrier plus data) signals at their outputs. The baseband outputs were treated differently at the two locations. At Parkes, the baseband signals were digitally recorded at the Mark III Data Acquisition Terminals (DATs) while simultaneously being transferred to CDSCC via the Telcom Australia microwave link. At CDSCC, the baseband signals from each of the three DSN antennas were first combined in the Baseband Combiner. The combined composite signal then followed two parallel paths. In one path, subcarrier demodulation and frame synchronization functions were performed by a Demodulation and Synchronization Assembly (DSA). After decoding and formatting, the data stream was returned in real time to JPL. On the other path, the baseband signal fed both a DAT (similar to the Parkes set-up) and a Long Baseline Baseband Combiner. It was in this latter combiner that the Parkes and composite CDSCC signals were finally brought together for baseband combining to provide the enhancement expected from the overall PCTA system. This operation was followed by data handling processes identical to those just described. A study of the diagram will show how the DATs allowed these same operations to be performed in non-real time whenever the need arose.

and Giotto spacecraft began in 1985. The Parkes antenna began supporting Voyager and Giotto passes in September 1985, following a final set of system performance tests to validate the end-to-end system and a few more weeks of operational verification testing to refine operations procedures. By the time the Voyager spacecraft began its observatory phase in November 1985, the PCTA was running in full operational status and providing the predicted downlink enhancement that was essential for the successful Voyager Encounter of Uranus on 4 January 1986.

At the range of Jupiter, 5 AU from the Sun, the maximum downlink data rate from the Voyager spacecraft had been 115.2 kbps. By the time the spacecraft reached Saturn, at a range of 10 AU, the maximum data rate had fallen to the range of 44.8 kbps to 14.4 kbps. When the distance doubled again to 20 AU at Uranus, the data rate would have been about one-fourth of that value, without the PCTA. The enhancement of the downlink provided by the PCTA allowed the mission controllers to recover telemetry virtually error-free from the spacecraft at data rates of 21.2 kbps to 14.4 kbps.

The demonstrated operational success of the PCTA during the Voyager Uranus Encounter confirmed the DSN's confidence in interagency arraying as a viable adjunct to the DSN capability for planetary missions. The future would provide two important occasions on which the DSN would have good reason to call on these techniques. The first would be to enhance an existing mission, Voyager at Neptune, the other to save a disabled mission, Galileo at Jupiter.

About the time that the PCTA technical studies were being completed in 1982, a broader based study of interagency arraying as a potential benefit to DSN capability for downlink support of planetary missions was initiated. Led by James W. Layland,38 this study was directed toward determining "which other facilities might be feasibly and beneficially employed for the support of Voyager at Uranus, and examining the Voyager/Neptune Encounter and such other future events and options as might appear." In light of subsequent events connected with the Galileo mission to Jupiter ten years later, this proved to be a very prophetic vision.

At its conclusion in early 1983, the study recommended that the existing plans for support of Voyager at Uranus should be completed. This culminated in the PCTA described above. The study also recommended that the arraying configuration for the Voyager Neptune Encounter should consist of the full array of DSN antennas, plus Parkes, plus the Very Large Array (VLA) at Socorro, New Mexico. There were some qualifications to these recommendations related to budget matters, but they did not affect the course

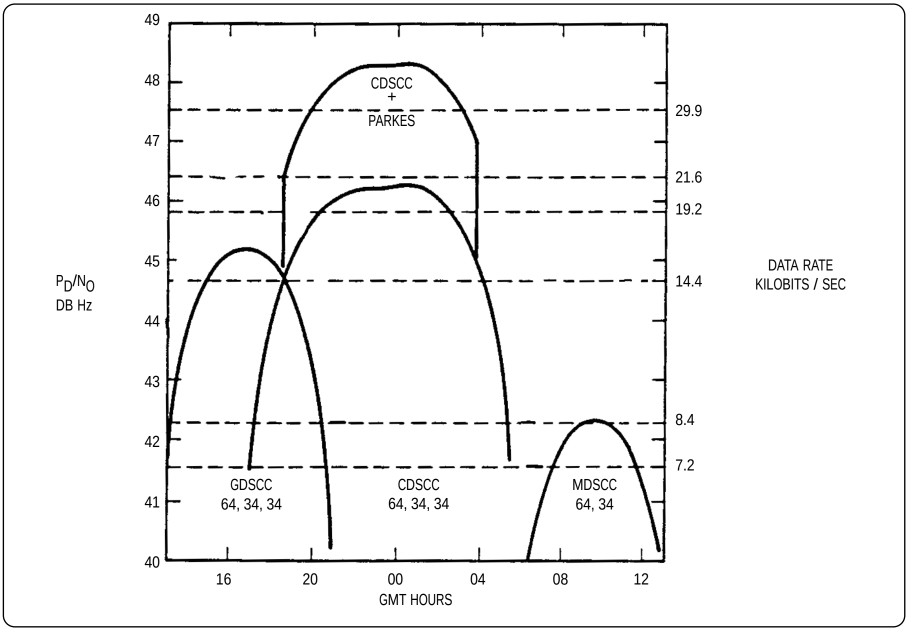

Figure 5-28. Enhanced downlink performance at Uranus.

of history. The comparative downlink performance data on which these recommendations were based are shown in Figures 5-28 and 5-29.

The recommendations from this study set the stage for the continuing DSN interest in interagency arraying and contributed materially to the success of the Voyager Encounter with Neptune in 1989, and eventually to the Galileo Encounter with Jupiter in 1996.

VLA-Goldstone Telemetry Array

Sponsored by the National Science Foundation (NSF) and operated by the National Radio Astronomy Observatory (NRAO), the Very Large Array (VLA) is a premier radio astronomy facility located at Soccoro, New Mexico. It consists of 27 antennas, each 25 meters in diameter, arranged in the form of a "Y" with a 20-km radius. This was the facility that, arrayed with the DSN antennas in Goldstone, California, would be known as the VLA-GDSCC Telemetry Array (VGTA).

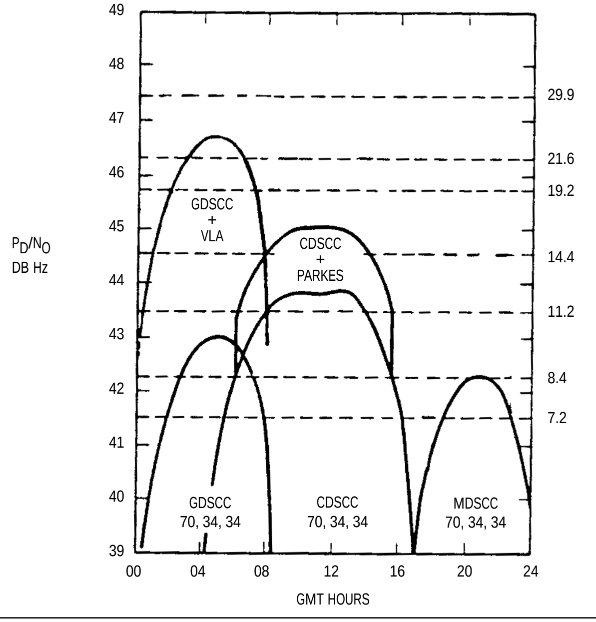

Figure 5-29. Enhanced downlink performance at Neptune. In these figures, each curve represents one of the array options from the study. The left-hand scale represents the performance of the downlink in terms of the ratio of data signal power (P_D) to noise power (N_O) expressed in dB. The right-hand scale shows the Voyager downlink telemetry data rates that correspond to the downlink performance values. These were the downlink data rates which theory predicted would be available 90 percent of the time when weather and other natural effects were taken into account. The reduction in downlink data rate that results from a 6-dB loss in downlink performance, which in turn corresponds to a doubling of Earth-to-spacecraft range, is very evident. The beneficial result of adding a non-DSN antenna to the existing DSN capability is represented by the performance curves. The bottom time scale shows the GMT time at which the Voyager spacecraft would be visible at each longitude during the respective encounters. These figures convey, in a very dramatic way, the essential reason for the strong DSN interest in the technique of antenna arraying.

The VGTA and its Australian counterpart, the PCTA, would be the DSN key to the Voyager Encounter with Neptune in August 1989.

By that time, the range to the spacecraft would have doubled again from 20 AU at Uranus to 40 AU at Neptune. Before that point was reached, however, the DSN 64-m antennas would have been upgraded to 70-m diameter and this, together with the two

34-m antennas and the VGTA, would more than double the downlink capability at Goldstone and offset the loss due to increased range. The PCTA would produce a similar result at the Canberra longitude. It was expected that these enhancements would support data rates at Saturn similar to those that had been used at Uranus, despite the increased range penalty.

By early 1985, a Memorandum of Agreement and Management Plan for a joint JPL-NRAO VGTA Project had been signed by NSF and NASA. The JPL TDA Engineering Office would have responsibility for overall planning and management, supported by implementation and preparation managers at JPL and NRAO. The JPL effort was led by Donald W. Brown, and the NRAO effort by William D. Brundage.[39]

Under the terms of these agreements, NASA agreed to bear the costs of installing low-noise, X-band amplifiers on all 27 VLA antennas, as well as the direct costs of preparing and operating the VLA for Voyager/Neptune support. This would include at least forty monthly tests with Goldstone between late 1984 and early 1989, in addition to forty spacecraft tracks during the Neptune Encounter period in late 1989.

The onsite engineering, installation, test, and operation of the PCTA were managed, as they had been for the Uranus Encounter, by the staff at the CDSCC in cooperation with the staff at Parkes.

A high-level block diagram of the VGTA is shown in Figure 5-30.

In the process of reaching the final operational configuration described above, a number of technical problems that were unique to the VGTA design demanded considerable attention before they were finally resolved.

The problems began with the low-noise front-end amplifiers for the VLA antennas. The baseline plan for the X-band low-noise receivers on the VLA antennas included cooled Field Effect Transistor (FET) low-noise amplifiers. By the time the first three receivers had been installed in 1985, new technology offered the promise of significant improvement in system noise temperature by the use of the High Electron Mobility Transistor (HEMT) low-noise amplifiers. This translated into an increase of 1.5 dB in the expected overall sensitivity of the VLA. As the HEMT amplifiers became available beginning in 1986, tests confirmed the expected improvements, and ultimately all of the VLA antennas were equipped with HEMT amplifiers. It was calculated that when equipped with HEMT receivers, the VLA would equal nearly three 64-m DSN antennas in terms of downlink performance, a valuable resource indeed.

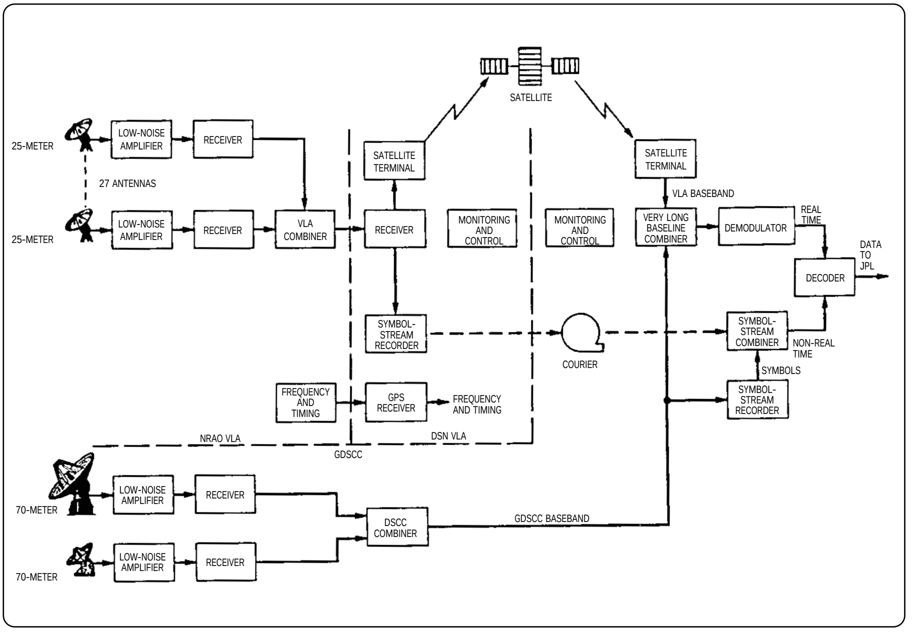

Figure 5-30. VLA-GDSCC telemetry array. In concept and operation, the VGTA closely resembles the PCTA described above. The essential features of the VGTA as eventually implemented were 1) X-band reception at the VLA and at GDSCC; 2) full-spectrum combining of 27 separate signals at VLA; 3) carrier demodulation to baseband at both sites; 4) transmission of the baseband signal from VLA to GDSCC via an Earth-satellite link; 5) standard baseband combining of one 70-meter and two 34-meter antennas at Goldstone; 6) baseband combining of the VLA and Goldstone signals in the Very Long Baseline Combiner at GDSCC; 7) convolutional decoding, signal processing, and data transmission to GDSCC to JPL; and 8) symbol stream recording at both sites to back up the real-time system and to allow for symbol stream playback and non-real-time combining at Goldstone.

For the combining (summing) process to work correctly, the signals from the twenty-seven separate VLA antennas must all be in phase with one another. By 1987, with the aid of new, more powerful computers at the VLA, phase measurements on all antenna baseline combinations could be made simultaneously. This allowed adjustments for phase variations along the signal paths to each antenna, caused by fluctuations in the troposphere, to be made in near-real time. The resulting ability to track out the effects of the troposphere, even in the severe summer thunderstorms characteristic of the VLA site, was instrumental in keeping the signal combining procedure working efficiently even in the worst summer weather experienced during the Neptune Encounter period.

An item of concern in the initial planning for use of the VLA for Voyager telemetry was the existence of a data gap in the signal output from each of the VLA antennas. The data gap was 1.6 milliseconds in length and occurred approximately 20 times per second. During the gap period, vital monitoring and "housekeeping" information passed between the VLA antennas and their remote control center.

Early studies (1982) of the effect of the "gap" on Voyager's coding scheme indicated that the error correcting capability of the outer Reed-Solomon code would bridge the gap and yield error-free performance, comparable to standard performance with perhaps 0.5 dB loss in threshold level for the combined VGTA output. These estimates were verified with simulated Voyager data and VGTA hardware and software during tests at JPL in 1985 and 1986.

The procurement and installation of a fully redundant Earth satellite link with dedicated transponders and Earth stations at each site were carried out by a contractor. Following the resolution of initial start-up problems and frequency response adjustments at both ends of the link, the performance of the satellite link was found to be similar to that of the microwave link associated with the PCTA.

During 1985, it became clear that the commercial power supplied to the VLA was too unstable to meet the DSN standards for primary power. Frequent voltage transients and outages occurred during inclement weather conditions. The operational deficiencies of the existing commercial power system were overcome by installing two diesel generators, each of 1,400-kW capacity, to provide primary power for the facility. This was followed by replacement of the deteriorating underground wiring that supplied power to the antennas out to the limit of the 20-km "Y" arrangement.

While an availability requirement of 80 percent was imposed on the PCTA Uranus Encounter configuration, the favorable experience led to an implicit design goal on the order of 90 percent for the entire VGTA for the Neptune Encounter. This required setting much higher reliability standards for the individual elements of the VLA system, including the twenty-seven individual antennas. In the beginning, it was not at all clear that thirty antennas (three DSN plus twenty-seven VLA) could be sustained and operated repeatedly with confidence in their reliability, given the diverse geographical and organizational aspects of the array. Because of these concerns, system reliability was given special attention throughout the implementation phase, and critical elements, such as an online computer and rubidium frequency standard, were provided by the DSN for use at the VLA.

The majority of the equipment supplied by JPL was installed at the VLA and Goldstone in late 1988. As each major assembly was completed, it was tested at the system level before being shipped to VLA or Goldstone for integration with the onsite systems. Monthly tests with the VLA and operational training at both sites continued through the year. These included demonstration tracks with all antennas on the Voyager spacecraft, where the array data was processed through the end-to-end system and delivered to the Voyager project for evaluation of its quality.

By May 1989, the VGTA was ready to provide full operational support to the Voyager mission as the spacecraft began its observatory phase of the mission. It was anticipated that, from this point on, the resolution in the Voyager images would exceed that of the best Earth-based observations. These expectations were completely fulfilled by the performances of the VGTA and the PCTA as the mission progressed. Some examples of the high-quality images that were downlinked at 21.6 kbps from Neptune were shown in Figures 5-7, 5-8, 5-9 of the Voyager section.

All of the careful, pre-Encounter preparations, enhanced by the proficiency of the NRAO and DSN operations personnel at the VLA and Goldstone, paid off handsomely during the Neptune Encounter. Statistics for the period 26 April through 28 September 1989 showed that during the forty Voyager Encounter passes supported in that period, the VLA signal to the DSN at Goldstone was available 99.959 percent of the time. As for the full VGTA and PCTA configurations which included the DSN antennas, data for the same period showed that more than 99 percent of the data transmitted by the spacecraft, from a distance of 40 AU, was captured by the Earth-based antennas of the interagency arrays.

The successful implementation and operation of interagency arrays in Australia and the United States provided a downlink with the capability of supporting telemetry from Neptune at 21.6 kbps for the full view period when the Voyager spacecraft was over Goldstone and Canberra (at the standard DSN 90-percent weather confidence level). Together with the expansion of the 64-meter antennas to 70 meters, interagency arraying had enabled a DSN downlink that effectively doubled the science data return from the Voyager Neptune Encounter.

The X-band Uplink

The arguments that drove the DSN to move from S-band to X-band for operation of their downlinks were not so compelling for the uplink. While the immediate improvement in downlink performance that followed directly from the frequency ratio of S-to X-band was of critical importance to the extension of DSN downlink capability to the outer planets, there were other means by which the S-band uplink capability could be extended. Prior to the early 1980s, improvement in uplink performance was achieved by increasing the power of the DSN S-band transmitters, first from 10 kW to 20 kW, then to 100 kW, and finally to 400 kW. At the same time, the effective radiated power in the uplinks was enhanced by the increased gain that resulted from the addition of new, larger antennas to the Network. Nevertheless, within the DSN Advanced Systems Development Section, a small (but very effective) X-band transmitter development program had been in progress for many years. This program was directed specifically toward supporting the DSN Planetary Radar program.[40] X-band transmitters had also been used to transmit timing signals from Goldstone to Canberra and Madrid by bouncing the time synchronization signal off the Moon.[41] These transmitters were designed for pulsed operation where, although the peak power level was hundreds of kilowatts, the average power was on the order of tens of watts. As distinct from planetary radar, planetary communications required continuous wave (CW) operation at the level of tens of kilowatts. The generation of tens of kilowatts of stable, CW, X-band power, and the power dissipation or cooling problems that were associated with it, was a challenging problem. The DSN needed a powerful rationale to embark upon such a task. It first appeared in 1978 with the gathering interest in the search for gravitational waves.

A proposal was made to detect gravitational waves by means of the Doppler signature imprinted on a CW, two-way radio link between Earth and a spacecraft crossing the interplanetary medium.[42] The key to success for such an experiment lay in the use of 1) a high frequency for the two-way radio path and 2) extremely high stability for the frequency of transmission. Together, this amounted to a requirement for a 20-kW, CW, X-band transmitter with a frequency stability of one part in ten raised to the power of fifteen (1×10^{-15}).

Apart from the potential for collaborating in a major scientific discovery, the DSN was highly motivated to gain the other benefits that were associated with a highly stable X-band uplink. These benefits related principally to improving the quality of the DSN radio metric data used for spacecraft navigation by effectively removing the transmission media effects. Improved accuracy of the DSN data would reduce the level of uncertainty in the orbit determination calculations, on which the spacecraft navigators depended for knowing the precise location of their spacecraft in interplanetary space.

The DSN undertook a phased development program in 1979 to add an X-band uplink capability to the Network. In the first phase of this program, an experimental model of an X-band transmitter and its associated equipment would be built and tested at DSS 13, the DSN's research and development station at Goldstone. In the second phase, a coherent X-band transponder would be added to an existing spacecraft prior to launch, to be used as an inflight technology demonstration of the end-to-end X-band system. The add-on would not interfere with operation of the spacecraft's normal S-band uplink.

By early 1981, a prototype 20-kW X-band transmitter and a highly stable exciter to drive it had been developed and were under test in the DSN labs at JPL. Also, arrangements were in place to add the X-band uplink to the NASA spacecraft, one of two spacecraft planned for the international Solar Polar mission to be launched in 1985.[43] The other spacecraft was to be provided by ESA and would eventually be renamed *Ulysses*.

Despite the cancellation of the NASA spacecraft in 1981, development of the experimental X-band uplink continued. At DSS 13, a full-scale ground system, including the Doppler extractors, X-band to S-band down-converter, and a Block III receiver, was set up and intensively tested. It was then planned to carry out the inflight X-band technology demonstration with the *Galileo* and *Venus Radar Mapper* (later called *Magellan*) spacecraft in 1984, using DSS 13 as the single ground station for the experiment.[44]

In a 3 June 1982 memo to the Assistant Laboratory Director for Telecommunications and Data Acquisition, the DSN Chief Engineer, Robertson Stevens, drew attention to the progress that had been made in the development of a stable X-band uplink at DSS 13. He also identified the advantages that would accrue from a move to X-band for operational use in the DSN. Relative to S-band uplinks, Stevens cited, as examples, improvements in range and Doppler measurements, immunity to signal distortion by charged particles along the transmission path, improved telemetry threshold in the two-way mode of Earth-to-spacecraft communications, and a tenfold improvement in command capability. Benefits not directly related to the uplink performance were to be found in lower cost spacecraft implementation and testing, as well as relief from future radio frequency interference problems.

He concluded by recommending that the operational Network should support the Galileo technology demonstration as a preamble to the initiation of a fully operational X-band uplink capability in the DSN.[45]

As a result, the DSN system engineering offices began writing technical requirements for the antenna, microwave, receiver/exciter, and transmitter subsystems that would be necessary to support the addition of an operational X-band uplink capability to the new 34-m high-efficiency (HEF) antennas, then being planned for implementation in 1984.

Shortly thereafter, Galileo was postponed to 1986 and Magellan to 1988, and the privilege of carrying out the first X-band uplink inflight demonstration fell to Galileo.

Frank P. Easterbrook and Joseph P. Brenkle made persuasive arguments for a joint Gravitational Wave Experiment (GWE) between Galileo (X-band) and Ulysses (S-band only), which provided the incentive needed to establish the GWE as a formal scientific endeavor,[46] as well as a technology demonstration as envisaged by the DSN.

In a carefully worded agreement that reflected the uncertainty of the times with regard to both budget and X-band operational performance, the DSN committed to implementing a 20-kW X-band uplink transmitter and three 34-m HEF antennas to support a technology demonstration which would include Doppler, ranging, two-way radio loss measurements, and commanding techniques.[47] It was believed that particular attention to phase stability would achieve a fractional phase stability approaching 5×10^{-15} to permit the detection of gravitational waves. The capability would be available in Canberra (DSS 45) in January 1987, at Goldstone (DSS 15) in July 1987, and in Madrid (DSS 65) in January 1988.

This plan was in process of being implemented when, as a result of the *Challenger* disaster in January 1986, both Galileo and Magellan were postponed to 1989, and Ulysses to 1990. In the aftermath of this affair, the HEF antennas were completed as planned, but the installation of the X-band uplink was deferred for about three years to meet a new set of requirements for the 1989 Galileo and Magellan missions. The new dates for the availability of an X-band uplink in the DSN were to be DSS 15 in March 1991, DSS 65 in September 1992, and DSS 15 in January 1993. In the meantime, a method was found for controlling the frequency and phase stability of the X-band transmitters to meet the stringent requirements imposed by the GWE.[48] Implementation progressed rapidly.

In fact, the X-band uplink at DSS 15 was completed and declared operational on 22 January 1990. By the end of the year, fully operational X-band uplinks were complete at DSS 45 and DSS 65. Tests were run to prepare them for the start of Galileo X-band operations when the high-gain antenna was unfurled in April 1991 for immediate support of Magellan. Ironically, *Galileo* never did get to use the X-band uplink because of the HGA failure as discussed earlier in this chapter. However, the spectacular success of the Magellan mission to Venus firmly established the X-band uplink as a powerful new DSN capability for Doppler, ranging, commanding, navigation, and radio science applications. The stringent requirements for X-band frequency stability were used to great advantage for very precise orbit determination and detection of gravity anomalies on Venus.

The early planning in 1994 for the new 34-meter beam waveguide antennas had made provision for 20-kW X-band transmitters. Budget considerations required these transmitters to include major components that were surplus equipment from tracking stations operated by the Goddard Space Flight Center. Subsequently, it was found that the effective radiated power needed to meet the technical requirements of future flight missions could be achieved with 4-kW, vis-à-vis 20-kW, transmitters on the new BWG antennas. Furthermore, the overall cost of installing new 4-kW transmitters was estimated to be about the same as retrofitting the surplus 20-kW transmitters. On these grounds, it was decided that the new BWG antennas would be implemented with 4-kW X-band transmitters and the work was re-directed accordingly.

By mid-1997, the X-band transmitters were complete at all three 34-m BWG antennas and, after a short period of operational testing, were put into service a few months later. The DSN could now operate two subnets of 34-m antennas with X-band uplink capability.

As the Galileo Era drew to a close in 1996, the X-band transmitters of the DSN were providing uplinks for Mars Global Surveyor, Mars Pathfinder, and Near-Earth Asteroid Rendezvous missions. In 1997, the giant *Cassini* spacecraft depended on X-band uplinks for its mission to Saturn. In 1998, Deep Space 1, the first of the New Millennium missions, and the Mars Surveyor Orbiter and Mars Surveyor Lander missions would also use X-band uplinks. Further into the future, long-term plans within the DSN called for 20-kW X-band transmitters on the 70-m antennas in the first years of the new millennium.

In 1997, 20 years had passed since the DSN, motivated by an interest in the search for gravitational waves, had moved toward X-band for its uplinks. X-band uplinks had become a reality; the improvements cited by Stevens in 1982 had all been fully realized, but the search for gravitational waves using this powerful medium for their detection remained a challenge for the future.

Block V Receiver

The Block V Receiver (BVR) was an all-digital receiver that had been under development as the Advanced Receiver and was characterized by high phase stability and extremely narrow tracking loop bandwidths, both highly desirable features for the Galileo and other weak downlink applications.[49]

The BVR first appeared for initial testing with the Galileo downlink at Goldstone in February 1994. As a result of these tests, some design modifications were made. In a further series of tests at the end of the year, the BVR successfully demonstrated its ability to track the weak Galileo downlink at all modulation settings, including the fully suppressed carrier mode. A telemetry data stream was flowed to JPL, and Doppler data were extracted and delivered to the Metric Data assembly. Repeated tests with the Galileo downlink in early 1995 confirmed the BVR performance under full operational conditions and showed excellent agreement with the performance predicted by theory.

Compared to the existing DSN Block IV receiver, the BVR showed greatly reduced high-frequency noise characteristics; it was virtually free of cycle slips even when the antennas were pointed close to the Sun, and noise in the Doppler data was reduced by at least a factor of three.

The role of the BVR in the development of the DSN Galileo Telemetry Subsystem (DGT) is described later. However, the new capabilities brought to the DSN downlinks by the BVR were not limited to its Galileo application. Its ability to track downlinks in the suppressed carrier mode; the extremely narrow bandwidth (about 0.1 Hz) of its carrier tracking loop; rapid, automatic signal acquisition; and great stability and versatility made it an obvious replacement for the older Block III and Block IV receivers throughout the Network. The time was propitious for the DSN to make such changes. The number of antennas in the Network had more than doubled in recent years, as had the number of simultaneous downlinks now handled by the DSN at each Complex. A separate receiver was necessary for each link, and the existing analog-based Block IV receivers were near the end of their lifespan. New receivers were needed, and the high-performance, multiple-function capability of the all-digital BVRs made them a logical choice for the new era. The 70-m antennas were equipped with BVRs in May 1995, followed by the 34-m HEF and 34-m BWG antennas a year later. A few of the old Block III and Block IV receivers were retained for use with the remaining SDA/SSA units on the 34-m STDN antennas and the 26-m Low-Earth Orbiter antennas.

The BVR not only performed residual carrier tracking, which was the only function performed by the Block III and Block IV receivers, but it also performed suppressed carrier tracking and carried out subcarrier and symbol demodulation functions. It therefore replaced not only the former Block III and IV receivers, but the former SDA/SSA and DSA units as well. In addition, it carried out the functions of signal estimation, Doppler extraction and IF signal distribution, thereby replacing the signal precision power monitors, Doppler extractors and IF distribution equipment that had been an integral part of the Mark IVA DSN.

The BVR accepted an S-band or X-band signal from a low-noise amplifier on the antenna to which it was assigned by the station controllers and, after performing the functions described above, distributed the following outputs for subsequent data processing:

1. two symbol streams to the assigned telemetry channel assemblies (TCAs) for decoding, frame synchronization, and telemetry data delivery;

2. two baseband outputs to the baseband assemblies (BBA) for combining with similar signals from other antennas;

3. two open-loop IF signals to other subsystems, such as radio science and VLBI, for special signal spectrum processing; and

4. two range-modulated signals to the Sequential Ranging Assembly (SRA) for ranging measurements.

Local Area Networks provided for communication and control between the BVR and other subsystems, and between the BVR and station controllers at the Link (LMC) or Complex (CMC) Monitor and Control level.

The DSN Galileo Telemetry (DGT) Subsystem

As it gradually became apparent that the Galileo HGA problem might not be corrected in time to save the mission as originally designed, attention began to turn towards viable options for continuing the mission in a modified form, using the spacecraft low-gain antenna (LGA).

In October 1991, the Telecommunications and Data Acquisition (TDA) Office at JPL chartered a thirty-day study to identify a set of options for improving the telemetry performance of the Galileo downlink at Jupiter, using the LGA, in the event that the HGA could not be recovered. The study team was led by Leslie J. Deutsch, Manager of Technology Development in the TDA Office.

The jobs of tuba player for a Dixieland jazz band and organist for a choir, church, and synagogue might seem unlikely roles for the mathematician most responsible for leading the DSN effort to recover the Galileo mission to Jupiter. However, all three roles were at one time played by Dr. Leslie J. Deutsch. Born and raised in Los Angeles, California, "Les" Deutsch spent much of his early professional life developing electronic music technology for his father's Deutsch Research Laboratories. After earning a doctorate in mathematics from the California Institute of Technology in 1980, Deutsch joined JPL in the Communications Systems Research Section, the section originally led by Walter K. Victor twenty years earlier. Deutsch became manager in 1986.

In 1989, he took charge of the Technology Development program in the Tracking and Data Acquisition Office, and it was while there that he brought the considerable resources of that group to focus on the Galileo problem. The full scope of the research carried out under that program is discussed separately in chapter 6.

A pleasant man of medium build, Deutsch always appeared to be busy. He was as much at ease discussing an abstruse mathematical representation of some physical problem in the DSN as he was executing a complex musical phrase on the pipe organ or tearing off a tuba riff in a jazz band.

In an interesting sidelight to his involvement with Galileo, Deutsch was invited to accompany a small party from NASA and JPL to Padua, Italy, in 1997 to participate in a "Three Galileos" conference. Sponsored jointly by the University of Padua, the German and Italian space agencies, and NASA, the conference honored "Galileo, the Man," "Galileo, the Telescope," and "Galileo, the Spacecraft." Deutsch contributed a technical paper[50] on the Galileo telemetry recovery effort. He was also honored with an invitation to present an organ recital in the Basilica of St. Anthony at Padua that featured music of Galileo's time. Dr. Deutsch continued to manage the program of technology development for the DSN until 1998, when he transferred to another area of JPL to study new technologies for planetary spacecraft.

Deutsch began by establishing a set of assumptions on which the team would base its considerations. Because of the HGA problem, all telemetry was being transmitted from the spacecraft on an S-band carrier through the LGA. The design of the spacecraft precluded the transmission of X-band telemetry through the LGA. If nothing was done to improve the S-band downlink performance by the time the spacecraft arrived at Jupiter in December 1995, the telemetry data rate would be only 10 bits per second, compared to the rate of 134,000 bits per second that had been designed into the original X-band mission.

The question facing the team was, "What could be done by making changes to the DSN or the spacecraft, or both, to improve this situation in the time available, and how much would it cost?"

Because the period of the study coincided with the Galileo Encounter with asteroid Gaspra, technical participation from the spacecraft and mission design areas was limited. Deutsch presented the team's report on 5 November 1991.

Out of the eight options that were identified, the following four were recommended for further evaluation:

Arraying Antennas

Increase the effective aperture area of the DSN antennas by building new ones or arraying existing DSN antennas with large, non-DSN antennas such as were then in operation in Australia, Japan, Germany, and Russia. In addition, the S-band performance of the existing 70-m antennas could be improved by installing special low-noise feeds called "ultra-cones."

Compression

Use data compression techniques on the spacecraft to increase the effective telemetry rate by reducing the number of data bits that needed to be transmitted for each image.

Coding

Improve downlink capability at low data rates by adding more advanced coding to the existing coded telemetry data stream. This would require inflight reprogramming of the spacecraft computers.

Modulation

Increase the effective power received by the ground antennas by changing the modulation index at the spacecraft transmitter to fully suppress the S-band carrier. This would have the effect of putting all the transmitted power into the subcarrier sidebands that carried the information content of the downlink.

Estimates of the performance gain, cost, and uncertainty associated with each option were made and evaluated. The study concluded by emphasizing the urgent need for the TDA and the Flight Project Office (FPO) to jointly develop a workable plan to implement the necessary changes in the spacecraft and in the DSN in the limited time available.

The positive results of the largely TDA-driven, thirty-day Galileo Options study, along with its emphasis on the need for timely action, led to the chartering of a further study which would involve both TDA and the Flight Projects Office (FPO). It was to be called the Galileo S-band Mission Study and would run from 9 December 1991 through 2 March 1992. The co-leaders of the study group would be Leslie J. Deutsch, representing TDA, and John C. Marr, Manager of JPL's Flight Command and Data Management Systems Section, representing FPO.

The objectives of that study were to

- assimilate and verify the information from the previous TDA Galileo Options Study;
- solicit additional ideas and assess their performance benefit and feasibility;
- create a conceptual design for the end-to-end telemetry system for the Galileo S-band mission;
- generate a rough cost estimate for this design for submission to the program offices at NASA Headquarters which were responsible for funding TDA (Code O) and FPO (Code S) in time for the Fiscal Year 1994 budget cycle; and
- make specific recommendations for the implementation of an end-to-end data system and hand these over to the organizations that would perform the work.

Whereas the TDA study had addressed only the high-rate science telemetry downlink, this study included real-time, low-rate science and spacecraft engineering data, uplink command and radio metric data, and navigation data. It also stipulated that no improvements to the downlink would be made until the important Probe science data had been successfully returned to Earth using the existing downlink capability.

The basic conclusion of the study was that a viable Galileo S-band mission was indeed feasible, based on a design that could meet a somewhat reduced, but still very acceptable, set of science objectives. Such a design could be implemented in time for the start of the Galileo orbital mission, and the total cost to NASA would be about 75 million dollars spread over seven years.

The results of the study were presented at NASA Headquarters on 20 March 1992 by Deutsch and Marr, supported by the Galileo Project Manager, William J. O'Neil, and the Galileo Project Scientist, Torrence V. Johnson.[51]

O'Neil came straight to the point. There was no way of knowing whether the HGA would eventually be deployed, he said, and NASA should therefore prepare to complete the Galileo mission with the spacecraft LGA. He said that a key design feature of the new LGA mission would limit the data return from the tape recorder to one full tape recorder load for each of the ten targeted satellite encounters. That feature, coupled with the proposed enhancement of the downlink by additions to the spacecraft and DSN, gave reason for great optimism that a worthwhile scientific endeavor could still be successfully accomplished.

In addressing the mission science objectives, Johnson demonstrated that the proposed LGA mission would, in effect, yield 70 percent of the science return expected from the original HGA mission. That new science, he said, would represent a major advance beyond the current level of Jupiter knowledge based on the results of the Voyager mission.

Marr described the reprogramming changes that would have to be made in the spacecraft computers to add the new data compression and encoding algorithms; he also described the costs, risks, and implication of these changes in data format on Galileo mission operations.

The four options recommended for enhancement of the downlink by the DSN were essentially a refined version of those that had originated in Deutsch's original study. Suppressed carrier modulation would yield 3.3 dB improvement; advanced coding, 1.7 dB; ultracones for 70-m antennas, 1.6 dB; and antenna arraying, 0-4 dB depending on which antennas were used. Together with the spacecraft modifications, these enhancements would provide a capability in the DSN to return one full load of tape-recorded data after each satellite encounter. They also satisfied the project requirements for receiving continuous engineering data and low-rate science data. The options for arraying antennas were not limited in this presentation to just the DSN. They included the cost of adding the large antennas at Parkes (Australia), Bonn (Germany), and Usuda (Japan) to the DSN arrays.

Following the presentations, action items to study three alternative approaches were assigned, and the JPL team returned to Pasadena to prepare for a final decision meeting set for 10 April 1991.

The three alternative approaches related to when and how the various arraying options would be implemented in the DSN. This decision largely affected funding profile issues that were of paramount importance in the NASA Headquarters view of the LGA mission.

The final meeting was attended by the newly appointed JPL Director, Edward C. Stone, in addition to the NASA Associate Administrators for Space Communications and Space Science.

While the previous meeting emphasized the technical aspects of the LGA mission and addressed the costs in a rather general way, this meeting concentrated specifically on costs and the time rate of expenditure that would be incurred by the three alternative approaches previously identified. Since support of the LGA mission would require so much 70-m antenna time at the expense of other ongoing and future missions, the issue of DSN loading was also included in the DSN presentation.

The major cost drivers for the DSN were known to be the decoder and decompressor, the ultracones for the 70-m antennas, the signal combiners, communication links between antenna sites, and the cost of renting time on whichever of the non-DSN antennas would be chosen for arraying. Except for the latter, each of the costs was well understood, easily identifiable, and bounded. The arraying costs were not.

At a breakfast meeting on the morning of the presentations, the new JPL director expressed concern over the uncertainty associated with arraying costs and the rather overwhelming number of options available to choose from. His concern prompted Deutsch to propose a last-minute option that he had budgeted out during an impromptu lunchtime session in a vacant office at NASA Headquarters. The "Deutsch" proposal limited all arraying operations to the Canberra site. The Australian antenna at Parkes would be the only non-DSN antenna used for arraying, and DSS 43 would be the only antenna fitted with an ultracone. This approach offered a more manageable proposal on which to base a decision and was included as part of the total DSN presentation. The total DSN-related cost was estimated to be 38.3 million dollars spread over the six fiscal years 1992 through 1997, with the major cost impact in 1994. The spacecraft and mission opera-

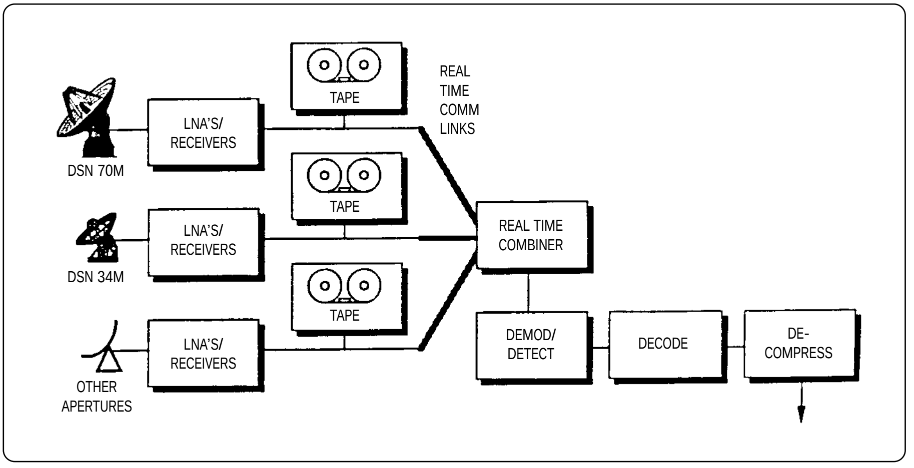

Figure 5-31. The concept of DSN telemetry for the Galileo LGA mission.

tions costs were 31.8 million dollars over the same period. This strategy was successful and was accepted as the way to recover the science data from Jupiter. Taken together, the spacecraft and ground system proposals would provide 70 percent of the original science data value at 1 percent of the original data rate for an overall cost increase of less than 5 percent.

The Galileo LGA mission as eventually approved by NASA satisfied most of the project requirements for real-time data and playback data return. It also provided for the new spacecraft capability but delayed the DSN enhancements until late 1996. It included DSN arraying centered on Canberra, as proposed by Deutsch. Software "hooks" were to be inserted in the design for the possible later inclusion of arraying with Parkes or Usuda, if funds could be identified.

The conceptual arrangement of telemetry proposed for DSN support of the Galileo LGA Mission is depicted in Figure 5-31.

Three types of receive antennas were to be used. These included the DSN 70-m antennas and the DSN 34-m antennas, with the non-DSN antenna at Parkes, Australia, as an option. Each antenna was to be equipped with a low-noise amplifier (LNA). The DSN 70-m antennas and the Parkes antenna would be equipped with ultracones and low-noise maser amplifiers, the others with cooled High Electron Mobility Transistor (HEMPT) amplifiers.

The LNAs were to be followed by receivers that would translate the incoming S-band signals to a lower frequency, filter out the uninteresting parts of the bandwidth, and digitize the resulting signal. The digital signals would be recorded on tape and sent to a central site for combining with the signals from the other antennas. There was also an option to send the digitized signal to the central site in real time.

At the central site, the signals from each antenna would be aligned with one another and combined (summed). The alignment would be accomplished by looking for the signature of the packet synchronization markers in the signals. The summed signal would then be demodulated. During much of the mission, there would not be enough signal strength to perform any demodulation before this summation. In some cases, data could be lost in the aligning process. When this happened, post-processing of the tape-recorded signals would be used to recover the data.

Following demodulation, the composite signal would be decoded in two stages. First, the effective (14, 1/4) convolutional code would be decoded. Then the Reed-Solomon code would be decoded. Finally, the effects of the two spacecraft compression algorithms would be undone in two decompressors. Subsequent processing of the science data would be performed by the Galileo Mission operations organization and the Science Teams.

From a technical point of view, the Galileo LGA Mission represented a remarkable episode of conceptual design in the areas of spacecraft data systems, planetary mission design, and DSN downlink engineering. However, before these concepts could become a reality, they had to be funded and implemented. While the NASA Headquarters people went off to wrestle with the funding problem on the short time scale required, the JPL people returned to Pasadena to initiate the implementation tasks.

Although we are only concerned here with the DSN effort, it needs to be said for the record that this evolution was an intensively interactive process. A satisfactory end result could only have been achieved by keeping all three elements—spacecraft, DSN, and mission operations—focused on the end-to-end performance of the downlink, while the implementation tasks proceeded as separate entities.

The task of implementing the DSN portion of the Galileo LGA mission was assigned to Joseph I. Statman, whose previous experience with developing the Big Viterbi Decoder for the original Galileo mission in 1989 was reported earlier. As Task Implementation Manager, Statman became responsible for transforming the conceptual ideas into hardware and software and installing and testing this equipment at the three DSN sites around the globe.[52] This task was to be accomplished within the cost estimates that had been presented to (and accepted by) NASA, and completed in time to support multiple Galileo Encounters with the satellites of Jupiter in less than forty-eight months. Although most of the technology was available, none of it had found practical application in this way, or on this scale, before. Some arraying technology had been used in the earlier Voyager encounters with Uranus and Neptune, and better techniques had been the subject of continuous study since then.[53] It had, however, been centered at Goldstone and had not involved intercontinental arraying between Goldstone and Canberra. The application of coding to enhance the performance of telemetry downlinks was well established in the DSN, and an advanced version of concatenated, convolutional coding had been added to the *Galileo* spacecraft downlink prior to launch.[54] This was intended for use at very high data rates (134 kbps) during the Io Encounter on the original X-band mission. Because it could not operate at the low data rates (10–100 bps) which would be typical of the LGA mission, it was of no further use. Nevertheless, the studies that had gone into developing that coding system were to be extended and applied in a new way to the LGA mission.[55]

Under the guidance of Statman, a comprehensive set of system and subsystem requirements and a cost breakdown for the DSN Galileo Telemetry (DGT) Subsystem, as it came to be called, was prepared and presented to a DSN Review Board for approval on 3 December 1992. Five days later, *Galileo* made its second and final close flyby of Earth and was on a direct path to Jupiter, just three years away. There was no time to lose.

In the course of transition from conceptual form to physical form, the DGT had been somewhat modified. Decompression of the received data function had become a Galileo mission operations function, and the arraying function had been limited to the one 70-m and three 34-m DSN antennas at Canberra. The combiner at CDSCC, however, was to make provision for combining the signals from up to seven antennas. This would permit a digitized signal from the DSN 70-m antenna at Goldstone to be added to the Canberra array to create real-time intercontinental arraying during Goldstone-Canberra overlapping view periods. The use of non-DSN antennas was not considered in this review.

The form in which the DGT was implemented at CDSCC is shown in Figure 5-32.

Although it was not considered part of the DGT, the Block V Receiver (BVR), shown in Figure 5-32, was an integral part of the DSN configuration for *Galileo*. Its primary purpose was to track the fully suppressed carrier downlink from a single 70-m antenna to extract telemetry and the two-way Doppler data essential for radiometric-based navigation of the *Galileo* spacecraft. When multiple-antenna arraying was used, the BVR provided Doppler data only and the DGT provided telemetry as described above. Its implementation proceeded in parallel with, but a year ahead of, the DGT.

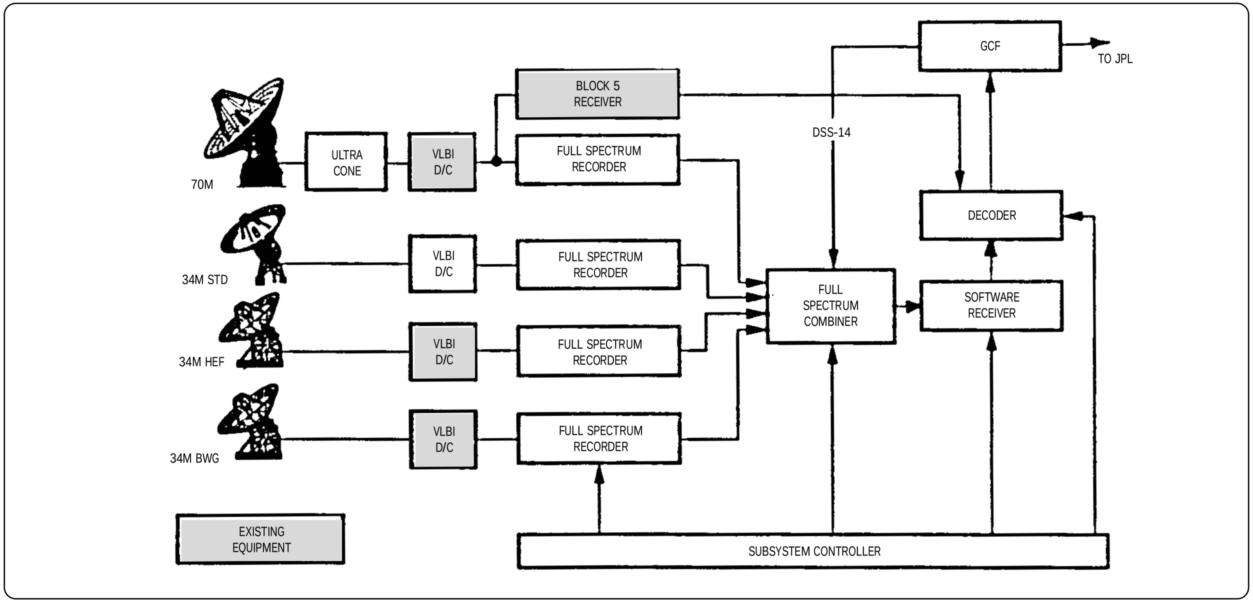

Figure 5-32. Functional diagram of the DSN Galileo Telemetry Subsystem for the Canberra Deep Space Communications Complex. The S-band signals from each of the antennas were first stepped down by 300 MHz to feed the Full Spectrum Recorders (FSR). After recording, the separate digitized signals were summed in a Full Spectrum Combiner (FSC) and delivered to a software receiver, where the detection and demodulation functions were carried out in a Buffered Telemetry Demodulator (BTD).[56] The complex decoding operation on the inner and outer codes was performed by a special Feedback Concatenated Decoder (FCD)[57] that delivered a decoded data stream to the ground communications equipment for formatting and transmission to JPL via the GCF. A system controller performed all the configuration and data management tasks via several local area networks. The arrangement at Goldstone was similar, except that there was no ultracone and no Full Spectrum Recorder. At Madrid, the arrangement was simpler still, consisting only of the decoder and system controller.

Repeated tests with the Galileo downlink in early 1995 confirmed the BVR performance under full operational conditions and it was accepted for future Galileo S-band mission support.

By May 1995, BVRs had been installed at all Complexes and soon demonstrated their ability to track the Galileo downlink in the suppressed carrier mode, deliver telemetry, and extract Doppler data.

In September 1995, based on these impressive results, the Galileo downlink was finally switched to the suppressed carrier mode that, supported with the BVR, would become the standard mode of operation for the rest of the mission. Less than three months later, *Galileo* arrived at Jupiter, relying on the BVR to track its low-powered S-band downlink and recover the most important data of the entire mission, the Probe entry science data. Over the next several months, the BVR lived up to everyone's expectations, and in recovering all of the Probe playback data, it allowed the Galileo project to accomplish its primary mission objective.

The tests conducted at Goldstone in early 1994 to demonstrate the BVR had also been used to demonstrate the proposed full-spectrum recording and full spectrum combining techniques[58] using prototypes of each of these elements of the DGT. The Galileo downlink signals from DSS 14 and DSS 15 were recorded simultaneously by the prototype FSR and were later combined with the prototype FSC.[59] The results were well within the predicted performance limits. Later experiments would verify similar performance in combining the downlinks from the intercontinental array of DSS 43 with DSS 14.

Over the course of the following two years, the operational versions of these units were built, installed, and tested at the Complexes. Since arraying was to be used only at Canberra, that was the only site where a full-spectrum combiner was installed. Also during this period, an ultra-low-noise, receive-only feed system (ultra-cone) was added to the Canberra 70-m antenna to reduce the S-band system noise temperature from its normal value of 15.6 kelvin (K) to 12.5 K. By reducing still further the noise on the downlink, this addition enhanced the performance of the downlink and increased the rate at which it could return data from the spacecraft. The DGT was rapidly taking real form and substance.

Although the DSN had received approval (and funding) from NASA Headquarters for the use of multiple-antenna arraying techniques to support the Galileo LGA mission, this support was limited to DSN antennas only. As design studies matured, however, it became evident that, even with the already-approved downlink enhancements in the DSN, the Galileo science data return would be especially low during the six-month period when the spacecraft was farthest from Earth, November 1996 through April 1997. This was the period when four of the ten satellite encounters would occur. Galileo and DSN concern with this situation in March 1994 led the TDA Executive Committee to recommend that the DSN array configuration planned for Canberra be augmented with the 64-m antenna of the Australian radio telescope at Parkes. The cost of making the necessary modifications to the DSN, making additions to the Parkes antenna, and renting time on this antenna was estimated at 4.3 million dollars. This would be met by funds transferred from the Galileo project. The estimated enhancement in data return was about 10 percent.

NASA approval was quickly followed by an Australian agreement to participate in the Galileo LGA mission, and the DSN began work on the changes needed to add Parkes to the Canberra array. Working arrangements with Parkes were quickly reestablished based on the agreements that had been made for Parkes support of the Voyager mission a few years earlier.

The DGT at Canberra supported the 70-m antenna, plus three 34-m antennas at CDSCC, plus the 64-m antenna at Parkes, in addition to the 70-m antenna at Goldstone whenever overlapping view periods permitted.

While DSN engineers had been focused on implementing the BVR and the DGT in the Network, the Galileo project focused on the changes that were required in the spacecraft to make the end-to-end downlink work. At the same time, the project had to carry the mission forward to the point at which the new flight software could be transmitted to the spacecraft. This point was reached on 13 May 1996, when the DSN began radiating a continuous series of commands to load the spacecraft computers with the new Phase II flight software. The continuous sequence was completed without incident nine days later on 22 May, and the spacecraft was enabled to begin operating in the new mode the following morning.

By that time the DGT, including the FCD decoder, was in place at all three Complexes and ready to handle the new concatenated convolutional (14, 1/4) coded downlink at all bit rates in the suppressed carrier mode.

The Ganymede Encounter on 28 June 1996 was the first critical test of the new flight software and the DGT ability to process it. Since it was not yet ready for full arraying, the DSN used single 70-m antennas to return the Encounter data. As the tape recorder playback data began to arrive over the new downlink for the first time, the Galileo project manager declared the images returned from the Ganymede Encounter to be “absolutely stunning” and a tribute to everyone involved in meeting the challenges of the LGA mission.[60] The end-to-end design of the new downlink had been proven in critical flight operations conditions, and the initial optimism for a successful conclusion to the Galileo Mission was fully vindicated.

The Callisto Encounter in November 1996 was the first occasion on which multiple antenna intercontinental arraying at CDSCC was used in critical real-time operations. The full DSN array capability, augmented with the Parkes antenna, allowed the *Galileo* spacecraft data rate to be raised from 40 bps to 120 bps during overlap periods. This Encounter, too, was extremely successful and demonstrated the full operational capacity of the DGT. Based on the performance of the DGT in supporting the Callisto Encounter, the ensuing recorded data playback, and confidence in the DSN ability to deal with the increased operational complexity of full array operations, the DGT and associated array mode was designated as the standard configuration for all subsequent Galileo operations in the DSN.

The operational complexities and remarkable downlink performance resulting from this arrangement throughout the rest of the Galileo mission were discussed earlier in this chapter.

Beam Waveguide Antennas

The weekly edition of "Significant Events in the DSN" for 29 August 1997 reported, "After successfully completing an extended series of mission verification tests on the X-band uplink and downlink capability, the 34-m beam waveguide antenna in Canberra (DSS 34), began operational tracking support this week. This antenna will now be available to provide support [to] such missions as NEAR, Mars Global Surveyor, Mars Pathfinder, and Cassini, in addition to continuing support for the Galileo array." It further reported, "System performance testing began on schedule this week on the new 34-m beam waveguide antenna in Madrid (DSS 54). This will be followed by mission verification testing prior to the antenna being scheduled for operational tracking support on 1 October 1997." And so they were.

Together with DSS 24 at Goldstone, which had been completed in February of 1995, the completion of DSS 34 and DSS 54 gave the DSN a full subnet of three 34-m beam waveguide (BWG) antennas, which represented a most significant increase in uplink and downlink capability.

Based on the successful design of the existing 34-m high-efficiency (HEF) antennas, the new BWG antennas now extended the existing DSN uplink and downlink capabilities on S-band and X-band to include Ka-band (32 GHz).

The design of the 34-m BWG antennas embodied the most advanced principles of antenna and microwave design. It also represented the culmination of nearly ten years of DSN engineering, research, and development, which began with a JPL report on Ka-band downlink capability for Deep Space Communications by Joel G. Smith in December 1986.[61]

In advocating the extension of DSN downlink, and ultimately uplink, capability to Ka-band, Smith argued that, just as the move from L-band (0.96 GHz) to S-band (2.3 GHz) had offered a possible increase in performance by a factor of 5.74 (7.6 dB), and the move from S-band to X band (8.4 GHz) a further increase of 13.5 (11.3 dB), the move from X-band to Ka-band (32 GHz) offered a potential increase in performance of 11.6 dB. These improvements were based on the theory that the capacity of a radio link between two well-aimed antennas is roughly proportional to the square of the operating frequency. In practice, the actual realizable gain is reduced by effects in the propagating media and losses in the various physical components of the link.

However, these latter effects could be controlled more easily at higher frequencies where microwave components, particularly the surface area of the antenna itself, could be smaller, stiffer, and mechanically more precise. Furthermore, measurements had shown that degradation of downlink reception at Ka-band, due to weather effects, was not as severe as had previously been thought.

Based on these considerations, Smith proposed a course of action which would culminate in an operational Ka-band downlink capability in the DSN by 1995. It began with the development of a new research and development antenna at Goldstone to "verify the various approaches to be used in upgrading the existing 34-m and 64-m/70-m antennas to good efficiency at Ka-band."

As Smith pointed out, there were other reasons, independent of the Ka-band decision, for building a new research and development antenna at Goldstone, but there was a strong synergism between the two.

In a companion paper,[62] Smith laid out all of the arguments for a new antenna, including those related to Ka-band, and proposed a specific design based on the existing HEF antennas but modified to incorporate new beam waveguide technology for the transport of microwave energy at low level (receiving) or high level (transmitting) between the antenna and the receiving or transmitting devices.

At that time, 1986, the beam waveguide concept had been around for several years, but it had not been employed in the design of any DSN antennas. It had, however, been used recently in the design of several major non-DSN antennas, most notably the 64-m antenna at Usuda, Japan, and the 45-m radio astronomy antenna at Nobeyama, Japan. R. C. Clauss had made an evaluation of these installations and became a strong advocate for the new technology.[63]

The supporting arguments included significant simplification in the design of high-power water-cooled transmitters and low-noise cryogenic amplifiers, improved accessibility for maintenance and adjustment, and avoidance of performance degradation associated with the accumulation of rain and moisture on the feedhorn cover. Beam waveguide technology allowed these systems to be located in a fixed, nonrotating area beneath the antenna azimuth bearing. As a result, the long bundles of power and signal cables and cryogenic gas lines that were required on the existing antennas could be replaced with short, fixed, nonflexing connections. Better frequency stability, higher reliability, and improved performance could be expected.

A beam waveguide system is shown in conceptual form in Figure 5-33.

The flat reflectors were used to redirect the beam; the curved reflectors were used to refocus the beam. As the antenna rotated in elevation, or azimuth, the transmitting or receiving beam of microwave energy was constrained to the beam waveguide path by the action of the reflecting and refocusing surfaces. The various reflectors were enclosed by a large protective tube or shroud along the beam waveguide path. Although this tube was a highly visible element of a BWG antenna, it played no significant part in the beam waveguide transmission process.

Over the next two years, 1989 and 1990, a design for a new BWG research and development antenna at DSS 13 was completed; funding was obtained; and construction of the new antenna commenced.[64] It would be located about 300 feet south of the existing 26-m antenna at the Venus site at Goldstone, and it was scheduled for completion in mid-1990. It was intended to serve as the prototype for a whole new generation of DSN antennas using the new BWG-type of antenna feed system.

The mechanical and microwave optical components in the BWG path are visible in the diagram of the completed DSS 13 BWG antenna shown in Figure 5-34.

From July 1990 through January 1991, the new BWG antenna was tested as part of its post-construction performance evaluation. Antenna efficiency (gain) and pointing performance measurements at X-band and Ka-band were carried out using unique portable test packages installed at either of the two focal points, F1 and F3. Celestial radio sources

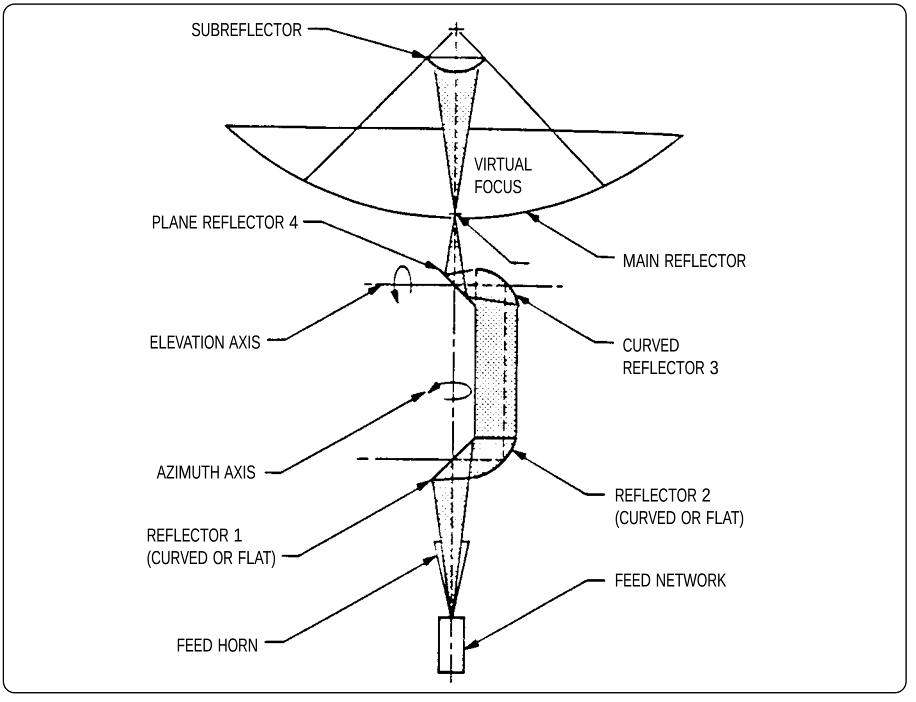

Figure 5-33. Beam waveguide antenna in conceptual form. In this diagram, Reflectors 4 and 3, mounted along the elevation axis of rotation, brought the beam from the subreflector on the main antenna down to the alidade structure. There, Reflectors 2 and 1, along the vertical axis, brought the beam to a stationary equipment room below the alidade that housed the transmitting and receiving equipment.

of known flux density were used in the calibration process. The values of peak efficiency of 72.38 and 44.89 percent, at X-band and Ka-band respectively, measured at the beam waveguide focus, met the functional requirements for antenna performance and agreed well with the predicted design values.[65] Further testing followed, as frequency stability, noise temperature, and the G/T ratio were evaluated and optimized.

Because system noise temperature is a critical parameter in deep space communication systems, the system noise temperature of the new antenna was of special concern. In the early tests, the system noise temperature was found to be higher than expected due to the spill-over losses of the BWG mirrors having a greater effect than previously thought.[66]

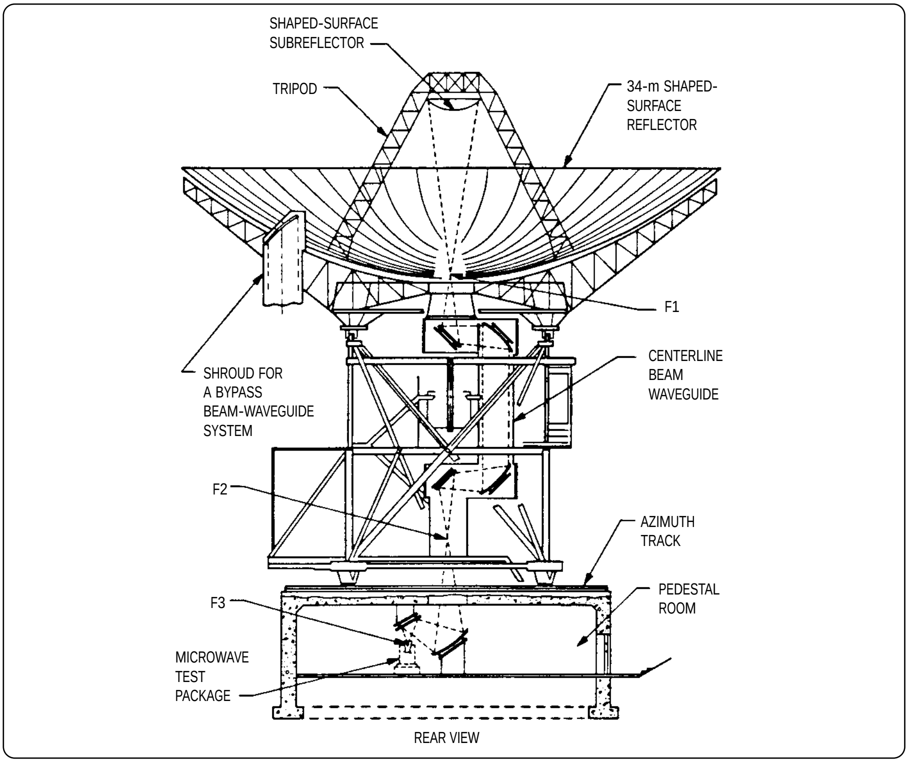

Figure 5-34. DSS 13 beam waveguide antenna.

New feedhorns were designed and tested and new methods for determining noise temperature in beam waveguide systems were developed.[67]

While the construction and testing of the prototype antenna at DSS 13 was in progress, submissions for funding for a fully operational version of a BWG at Goldstone (DSS 24) were being made. At this time, the Galileo mission to Jupiter was progressing normally and the high-gain antenna had not been deployed. The planned close flyby of Io in December 1995 over Goldstone demanded the full X-band support of the 70-m and HEF antennas at Goldstone, leaving little or no resources for other flight projects. Using this as justification, further funding for two more BWG antennas was requested from NASA Headquarters and, at the expense of some institutional compromises, was awarded. Now there was funding for a cluster of three BWG antennas at Goldstone, DSS 24, DSS 25, and DSS 26. These were placed on contract with an American construction

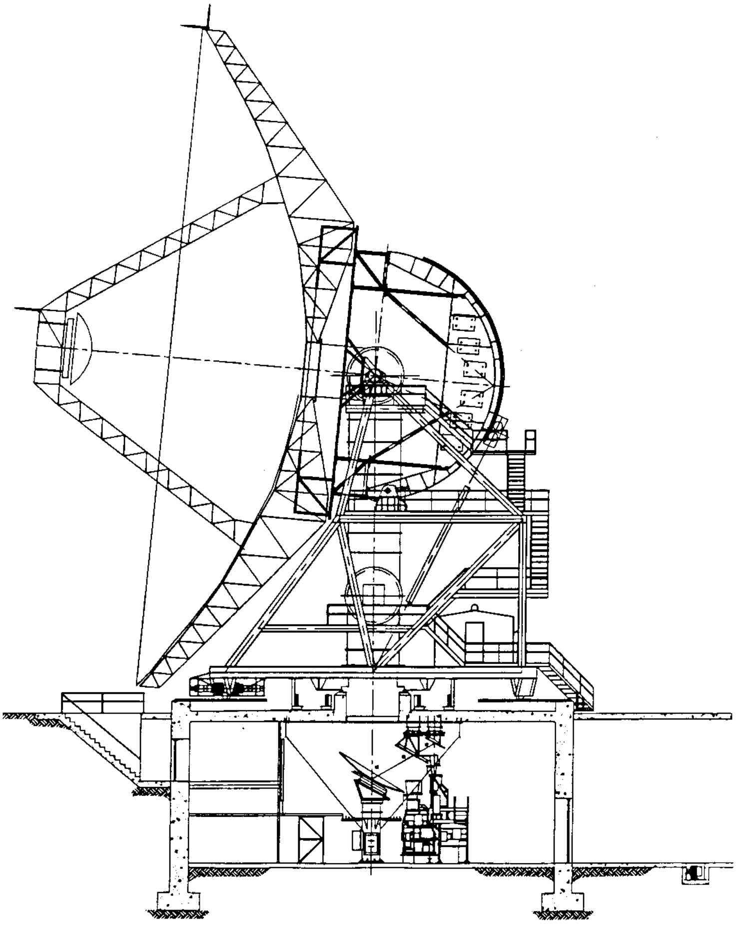

Figure 5-35. Design for operational 34-meter beam waveguide antenna. In the operational version of the 34-m beam waveguide antenna, the alternative bypass microwave system was eliminated and the alidade structure was strengthened to add stiffness and to accommodate the additional drive and ancillary services.

company, TIW Systems, Inc. All three antennas would be located in the Apollo Valley at Goldstone, and work began immediately.

By the time construction began, the original design for the DSS 24 antenna had been modified to incorporate many of the lessons learned from the DSS 13 experience and the intensive program of performance measurements that had been conducted on that antenna. In particular, the antenna structure had been modified to improve its "gravity performance" by controlling the antenna distortion for best fit to the ideal parabolic shape, as the antenna moved through the full range of elevation angles. Other improvements related to the azimuth cable wrap-up and to the substitution of nonmechanical "RF Choke" bearings for the mechanical tube bearings used at the rotating junctions of the waveguide shroud. Also, the four large (30-inch diameter) wheels which supported the alidade structure on the azimuth track had been "surface hardened" to improve wearability, based on operational experience with the existing HEF antennas. After a short period of use, these wheels cracked and had to be replaced with "through hardened" wheels to stand up to the loads and wear induced by continuous use under operational conditions. The design features of the operational version of the DSN 34-m BWG antenna are illustrated in Figure 5-35.

Construction of DSS 24 began in February 1992 with the blasting of a large hole, 30 feet deep and 60 feet in diameter, into solid bedrock to accommodate the pedestal room with its 24-ft- high ceiling. Because this was the first antenna to be built, it revealed the presence of several unsuspected problems in design and planning and, acting somewhat as a pathfinder for the others, was not completed until May 1994.

Microwave performance testing of the new antenna was carried out during the summer of 1994 using the same techniques that had been employed at DSS 13. Antenna efficiency, pointing calibrations, and system noise temperature were all included at S-band, X-band, and Ka-band.[68] In addition, microwave holography was used to adjust the reflector panels on the main antenna for optimum efficiency.

The values for gain and efficiency obtained from these tests are tabulated below:

DSS 24 Peak Gains and Efficiencies

Band, Frequency (GHz)	Gain (dBi)	Efficiency (percent)
S, 2.295	56.79	71.50
X, 8.45	68.09	71.10
Ka, 32.00	78.70	57.02

The results of these measurements confirmed the soundness of the basic design and the improvements that had accrued from the modifications mentioned above.

Experience gained from the DSS 24 task enabled the remaining two antennas to be built in a parallel fashion to save time. They were completed in July and August 1996, respectively, about 18 months after construction started in 1994.

Unlike DSS 13, which was built for deep space communications research and development purposes, the other BWG antennas were intended for operational use in the Network. Consequently, after the construction phase was completed, they were subjected to an intensive program of testing under operational conditions before they were declared operational and accepted for tracking flight spacecraft as an element in an array or in a stand-alone mode. The "operational" dates for all the BWG antennas are given in the table below, and they generally followed the completion of the antennas by several months.

DSN plans for BWG antenna construction in Spain and Australia were significantly affected by the dramatic events, described earlier, that occurred on the *Galileo* spacecraft in April 1991. To save the mission, DSN and Galileo engineers had proposed an alternative mission using the spacecraft's S-band, Low-Gain Antennas and an array of S-band antennas in Australia. This situation provided the DSN with the high-profile justification needed for adding a fourth BWG antenna at Canberra (DSS 34). With design and specification details already available from the Goldstone task, funding for construction of this antenna was quickly approved.

International bidding was opened for the erection of a fourth BWG antenna in Australia with an option for two more when funding became available. (It was recognized that significant savings could be realized by building the antennas in groups of three). The contract was won by the Spanish firm Schwartz-Hautmont, and construction began at the Canberra site in July 1994.

Initially, problems with water percolation in the large excavation for the pedestal room, along with difficulties with the contract and Australian unions, caused significant delay to the construction schedule. Eventually these problems were dealt with, work resumed, and the antenna was completed in November 1996, very close to the original schedule. After a short period of operational testing, the antenna was accepted for operational support and immediately began supporting Galileo on S-band as part of the Canberra array. Later, the X-band uplink was added, and after a period of mission verification testing, it began operational tracking support with X-band uplink and downlink in August 1997, as mentioned above. A photograph of the completed antenna is shown in Figure 5-36.

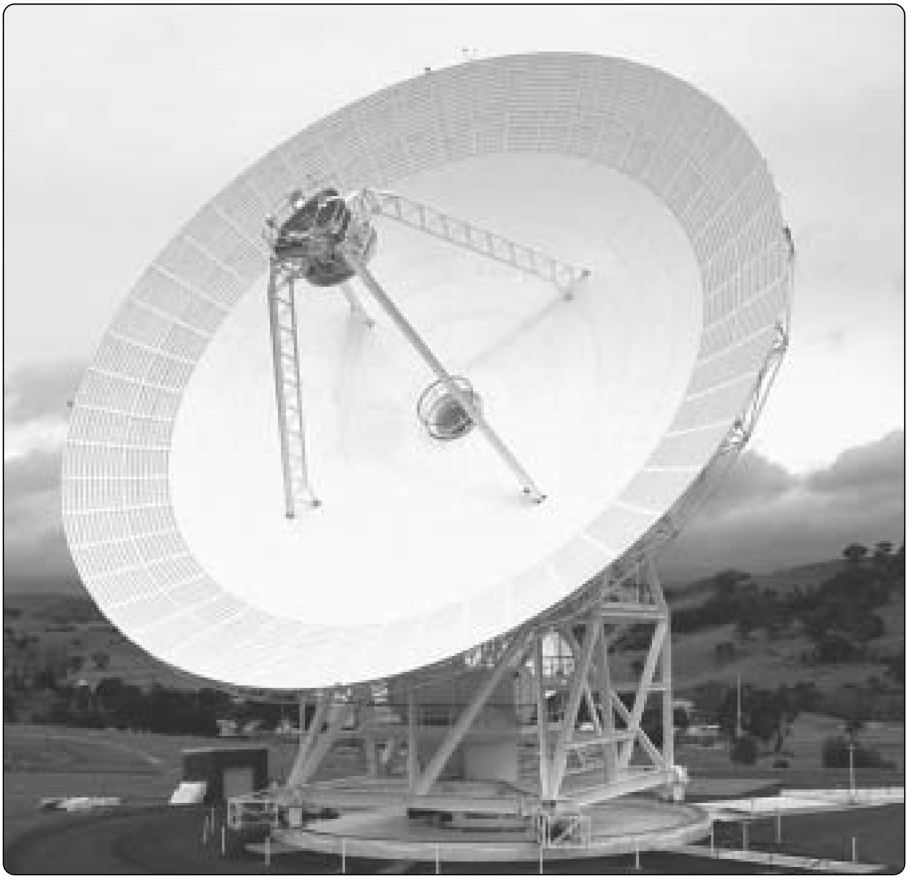

Figure 5-36. DSS 34 BWG antenna at the Canberra Deep Space Communications Complex, Australia, 1996.

Two years after the Galileo high-gain antenna problem changed the course of BWG history in the DSN, another spacecraft event occurred which once again changed the course of the program.

In August 1993, eleven months after launch and three days before insertion into Mars orbit, communication with the *Mars Observer* spacecraft was lost and never recovered. In the aftermath of this loss, NASA hastily proposed and funded a new mission to Mars to be called *Mars Global Surveyor* (MGS). Its arrival at Mars toward the end of 1997 would be just in time to create a conflict for X-band uplink support over Madrid with the *Cassini* spacecraft scheduled for launch in October of that year. Once again there was a strong programmatic need for an additional BWG antenna in the Network, this time at the Madrid site. But this time, there was no funding immediately available. Fortunately, the DSN was able to reprogram sufficient money saved from the contracts for the first and second groups of three antennas to fund the option for the fifth BWG antenna at Madrid. The contractor, Schwartz-Hautmont, began construction in June 1995. Despite a water problem similar to the one that had occurred during construction in Australia, the antenna was completed by August 1997. System and mission verification tests followed, and the antenna was accepted for operations support in October 1997.

To a large degree, the disposition of S-band and X-band capability among the different BWG antennas was driven by the funding available for procurement of the necessary electronics packages. Although all of the antennas were capable of operation at Ka-band, the use of Ka-band for spacecraft telecommunications links, except for *Cassini*, had not matured beyond the need for a demonstration capability at one BWG antenna by the end of 1997. The need for a full subnet capability was expected to develop in the years ahead. A Ka-band downlink capability existed only at DSS 25.

In late 1994, two 34-m BWG antennas that had formerly belonged to the U.S. Army and were situated near the Venus site at Goldstone were transferred as surplus property to JPL. On transfer to the DSN, they became identified as DSS 27 and DSS 28 and were designated as High Speed Beam Waveguide (HSB) type. These antennas were azimuth/elevation mounted and, before they could be put into service, had to be stiffened and strengthened to meet DSN standards for reliability and stability under conditions of continuous use. DSS 27 was equipped to provide backup for the one remaining 26-m at Goldstone, DSS 16, and to supplement DSN capability for high-Earth orbiter missions like Infrared Space Observatory (ISO) and Solar Heliospheric Observatory (SOHO). DSS 27 thus became a 34-m BWG that had the performance of a 26-m S-band antenna with one multifunction receiver and a low-power, 200-W transmitter. Like DSS 16, it was operated remotely from the SPC located some ten miles away from the antenna site. Activation of DSS 28 was postponed for later, when funding for suitable electronics would become available. The photograph in Figure 5-37 shows a cluster of three 34-m BWG antennas at Goldstone in 1995.

The times at which the various BWG antennas came into operational service in the Network and their uplink and downlink operating bands as of December 1997 are summarized in the table below.

Figure 5-37. Cluster of three 34-m BWG antennas at Goldstone, 1995.

DSN 34-Meter Beam Waveguide Antennas

DSS	In Service	Uplinks	Downlinks
13*	July 1990	S, X, Ka	S, X, Ka
24	Feb. 1995	S	S, X
25	Aug. 1996	X	X, Ka
26	Aug. 1996	X	X
27	July 1995	S	S
28	Oct. 2000	N/A	N/A
34	Nov. 1996	S, X	S, X
54	Oct. 1997	S, X	S, X

* DSS 13 for research and development use only.

N/A: Electronics not available as of January 1998.

With the completion of DSS 54 in 1997, the DSN finally had a complete subnetwork of three 34-m BWG antennas, all of which were capable of operation at S, X, and Ka-band. By then, the trend for future missions was towards shorter passes and higher data rates, a natural application for Ka-band uplinks and downlinks, as Joel G. Smith pointed out in the 1988 papers described earlier. In this context, the DSN was well positioned to cope with mission requirements in the immediate future. The possibility of a justification for more antennas seemed unlikely, and in terms of antennas, the DSN had reached a plateau that appeared to extend well into the foreseeable future.